Automatic Vehicle Identification Technology Applications to Toll Collection Services

JIAN JOHN LU, MICHAEL J. RECHTORIK, AND SHIYU YANG

Intelligent transportation systems technologies are being developed and applied through transportation systems in the United States. An example of this type of innovation can be seen on toll roads where a driver is required to deposit a toll in order to drive on a toll road. To automatically process toll services, automatic vehicle identification (AVI) technologies should be developed and implemented. A summary is presented of a study that focused on the performance analysis of three types of AVI technologies that could be used for toll collection applications on the Crosstown Expressway and the Veterans Expressway in Hillsborough County, Florida. The three AVI technology types were optical/laser scanner, radio frequency, and inductive loop. The study aimed at analyzing the total average delay and AVI market share due to the usage of AVI technologies. Delay performance and market share resulting from the application of each AVI technology type were used to compare the effects of different AVI technology types. The analysis was based on computer simulation using an AVI lane choice model (demand model) and a delay model (performance model) with the data collected from the two toll roads in Hillsborough County. From the simulation results, a cost-benefit analysis was performed to evaluate the impacts of AVI technologies on the ratio of benefit over cost. Results of the cost-benefit analysis can be used to determine the optimal configuration of AVI lanes and manual lanes. A procedure is provided that can be used for planning and designing AVI technologies used in toll service.

Intelligent Transportation Systems (ITSs) introduce advanced technologies to transportation systems to improve safety and capacity, reduce congestion, enhance mobility, provide security, allow fuel savings, and minimize environmental impacts. An area of surface transportation systems in which this can be seen is on toll roads. Automatic vehicle identification (AVI) techniques to identify vehicles as they pass specific points without requiring any action by the drivers have been tested and are being implemented through the United States.

Four AVI technologies are being developed and implemented: optical/infrared (barcode), inductive loop, radio frequency (RF), and surface acoustical wave (SAW). The barcode technology uniquely identifies a vehicle using a laser scanner to scan a barcode sticker located on the vehicle. The inductive loop technology uses an antenna embedded in the pavement at the toll station. A transponder mounted on the underside of a vehicle communicates with the antenna. The RF microwave technology employs microwave frequencies to a transponder located in the vehicles. This transponder is different from the one used in the inductive loop technology, since it contains a small internal receiving antenna and an internal transmitter. Similar to the RF technology, since it operates with microwave frequency, the SAW technology uses a low-power RF signal from the AVI reader that is captured by the transponder antenna, energizing a lithium crystal, which sets up a SAW.

AVI technology has the potential to increase the capacity of a toll lane. However, the increased capacity may not necessarily increase the throughput of the station. To make the application of AVI technology more cost effective, the technology should be consistent with the market share that AVI lanes will take in total usage. The market share depends on the price of AVI equipment, the overall performance of the toll station, and travelers' attributes in choosing AVI lanes. Different combinations in toll collection methods will generate different capacities for a toll station and will result in different operational performance under different market share conditions.

Before AVI technologies can be implemented to a toll road, the roadway needs to be analyzed to determine if the volumes support AVI. Certain volume thresholds have been developed for AVI implementation:

- Mixed AVI: 3,000 vehicles per hour (vph),
- Dedicated AVI: 5,000 vph,
- Express AVI: 7,000 vph.

These thresholds are based on a 30 percent participation rate of AVI users. A 30 percent participation rate is an average percentage that has been seen on other AVI technology toll roads.

The technology and political issues related to applying AVI technology to toll roads must be explored. As stated by ITS America, critical issues include design, performance, violation enforcement, marketing, cost-benefit, and standard specifications (*1*). To explore these issues, many studies have been conducted (*2–6*). In 1994 TRB published an NCHRP synthesis written by Pietrzyk and Miezejewski to summarize technologies used in electrical toll and traffic management and related projects (*7*). In the past several years, Florida has been one of the few leading states that have implemented and tested AVI technologies for toll collection. The Center for Urban Transportation Research (CUTR) has conducted several research studies sponsored by the Florida Department of Transportation (FDOT) to evaluate electronical toll collection technologies on Florida's turnpike (*8,9*). The technical performance of different AVI technologies was evaluated in the field by CUTR researchers and FDOT engineers. These studies provide technical background for future applications of AVI technologies to toll collection services.

The capacity performance of a manual lane and an AVI lane at a toll collection station has been discussed in several documents

J. J. Lu and M. J. Rechtorik, Department of Civil and Environmental Engineering, University of South Florida, Tampa, Fla. 33620. S. Yang, Department of Survey, Tongji University, Shanghai, China.

(*8,10,11*). According to these previous studies, the capacity performance of a manual lane and an AVI lane using different AVI technologies is given in Table 1. The capacity of a manual lane was the average of the capacities of the following facilities: manual normal, manual no change, manual ticket, manual coin, and manual token.

As stated previously, one of the issues to be explored is the cost-benefit analysis of the toll collection stations that employ AVI technologies. Results of the cost-benefit analysis would help the planning and design procedures of electronical toll collection stations using AVI technologies. On the other hand, use of AVI technologies will result in improved capacity performance and reduced congestion at a toll collection station. This paper summarizes a study that analyzed the impacts of AVI technologies on the total average delay of vehicles at the toll collection stations on the Crosstown Expressway and the Veterans Expressway in the Hillsborough County, Florida. In addition, a cost-benefit analysis was performed to evaluate the effects of AVI technologies on the ratio of benefit over cost. On the basis of the cost-benefit analysis, an optimal number of AVI lanes was determined in this paper. More specifically, several models—including a lane choice model (demand model), a delay model (performance model), and a procedure to solve equilibrium status—were used to simulate the total average delay of vehicles to pass the toll collection stations and AVI lane market share rates. Results from the simulation were used to analyze the cost-benefit performance of the toll collection stations using AVI technologies. The AVI technology types evaluated were the optical/laser scanner, inductive loop, and radio frequency. Field data were collected from the toll collection stations on the Crosstown Expressway and the Veterans Expressway.

DATA COLLECTION

Toll Stations

The Crosstown Expressway starts in south Tampa at Gandy Boulevard and runs northeast until downtown Tampa, then runs east through Brandon and terminates at I-75. The main-line toll station is located east of 50th Street and west of 78th Street in east Tampa. The Veterans Expressway starts at SR-60 and runs north, terminating at Dale Mabry just south of Passco County. The main-line toll station is located at the Anderson Road exit in north Tampa. Figure 1 illustrates the locations of the Crosstown Expressway and the Veterans Expressway.

To perform this analysis, existing lane configurations for the main-line toll stations were collected in each direction. The main-line toll station on the Crosstown Expressway contains six lanes in the eastbound direction and seven lanes in the westbound, with a reversible lane in the middle. The reversible lane provides an additional lane in the westbound during the morning peak hour and an additional lane in the eastbound during the afternoon peak hour. The main-line toll station on the Veterans Expressway contains eight lanes in both the northbound and southbound directions, with a reversible lane in the middle that provides the ninth lane in the peak direction.

TABLE 1 Approximate Capacities of Toll Lanes

Collection Method	Passing Speed	Capacity
Manual	Very Slow	770 vph
AVI-Optical Scanner	Slow	1200 vph
AVI-Inductive Loop	Moderate	1400 vph
AVI-Radio Frequency	Fast	1600 vph

Traffic Conditions

During the week of April 15–19, 1996, directional traffic counts were performed at the Crosstown Expressway and the Veterans Expressway. From existing traffic volume data, the Crosstown Expressway had a daily traffic volume of approximately 33,500 vehicles, while the Veterans Expressway had a traffic volume of approximately 23,750 vehicles. Table 2 summarizes the results of the traffic count. During the morning and afternoon peak hours, all of the toll stations in the peak directions were opened to vehicles. Some vehicle delay and queueing were experienced during peak hours because of increased average times spent paying tolls.

ANALYSIS ON DELAY AND MARKET SHARE

This analysis was to use simulation models to evaluate the impacts of AVI technologies on the total average delay and AVI lane market share of the drivers using the toll collection stations on the Crosstown Expressway and the Veterans Expressway. The simulation models that were used in the analysis included a performance model (delay model), a lane choice model (demand model), and a procedure to solve the equilibrium status. The simulation analysis was based on the current conditions of the toll collection stations on the two toll roadways.

Model Description

Delay and lane choice models used for toll collection simulation have been used in past studies (*10,11*). These models are based on the queue model and the logit model and are described as follows.

Lane Choice Model (Demand Model)

With the lane choice model, a relationship of travel demand with a specific AVI lane designation configuration, service quality, and the cost of AVI devices installed in the vehicle is established. Many attributes would have influence with this model. Typical attributes include performance and cost. In this analysis, drivers selected two alternatives: manual lane or AVI lane. Utility functions are used to represent linearly the effects of the attributes on the selection behavior. The utility functions for the two alternatives are

$$V_a = k_1 + k_2 T_a + k_3 N_a + k_4 C_a \tag{1}$$

$$V_m = k_2 T_m + k_3 N_m \tag{2}$$

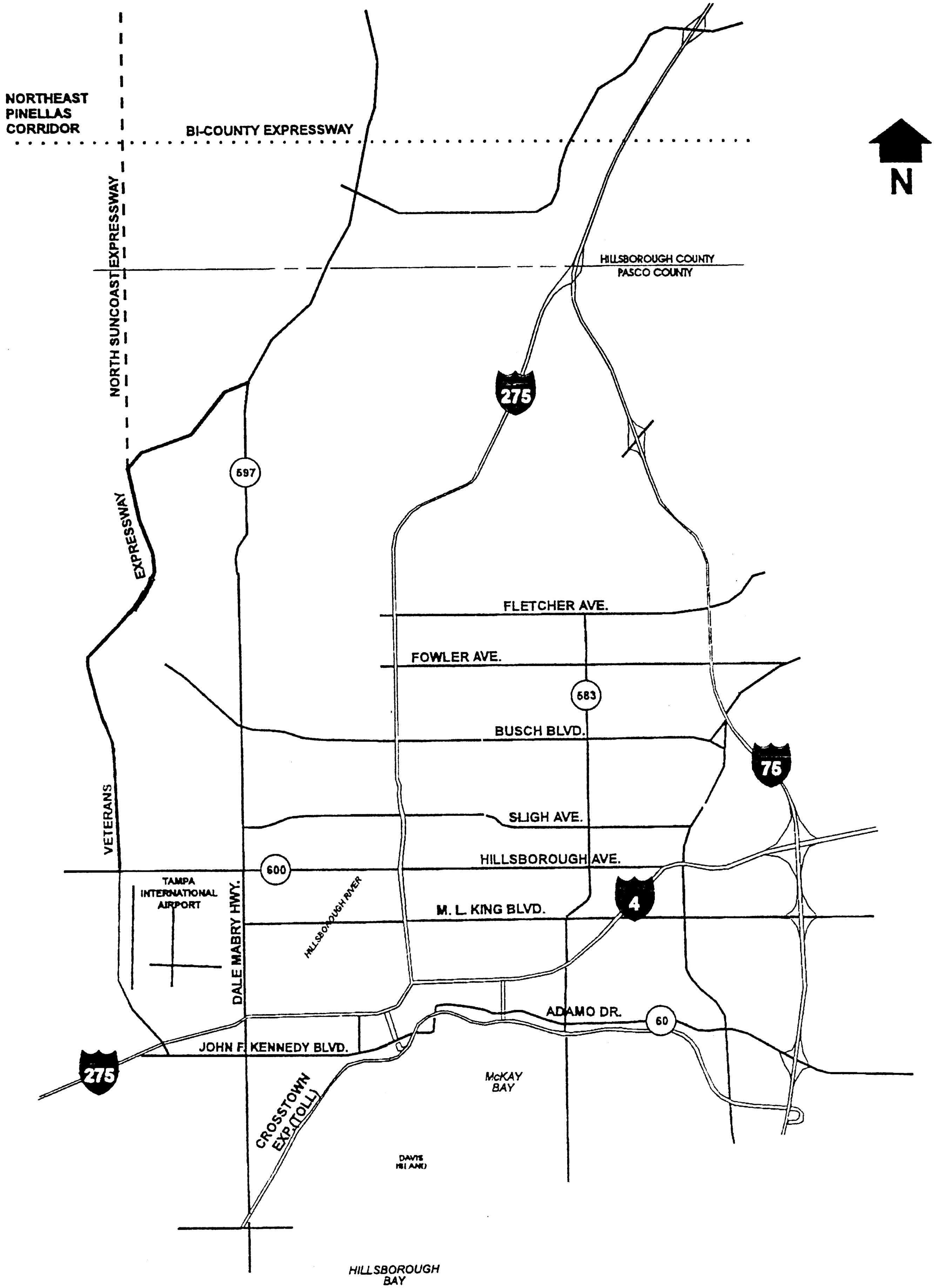

FIGURE 1 Locations of Crosstown Expressway and Veterans Expressway.

TABLE 2 Summary of Traffic Counts

Roadway	Traffic Volume During Peak Hour			
	Morning Peak Hour		Afternoon Peak Hour	
Crosstown Expressway	EB	840 vph	EB	2913 vph
	WB	3594 vph	WB	1167 vph
Veterans Expressway	NB	646 vph	NB	2104 vph
	SB	2635 vph	SB	831 vph

where

V_a = utility of selecting AVI lane,
V_m = utility of selecting manual lane,
T_a = total average delay of vehicles using AVI lanes (min),
T_m = total average delay of vehicles using manual lanes (min),
N_a = number of AVI lanes at toll collection station,
N_m = number of manual lanes at toll collection station, and
C_a = cost of AVI devices installed in vehicles ($).

The constant parameters (k_1, k_2, k_3, k_4) are used to weigh the attributes in the utility functions. This analysis was performed by using the logit model with the market share estimated by the following equations:

$$P(a) = \frac{e^{V_a}}{e^{V_a} + e^{V_m}} \tag{3}$$

$$P(m) = \frac{e^{V_m}}{e^{V_a} + e^{V_m}} \tag{4}$$

where $P(a)$ is the percentage of the drivers who would select an AVI lane and $P(m)$ is the percentage of the drivers who would select a manual lane.

If the directional traffic volume using a toll collection station is symbolized by Q, then the traffic volume using AVI lanes, symbolized by Q_a, and the traffic volume using manual lanes, symbolized by Q_m, can be estimated by the following equations, respectively:

$$Q_a = QP(a) \tag{5}$$

$$Q_m = QP(m) \tag{6}$$

where

$$Q_a + Q_m = Q$$

and

$$P(a) + P(m) = 1$$

In this analysis, the main attributes that affect driver behavior to select an AVI or a manual lane include total average delay, number of available AVI or manual lanes, and cost of AVI devices installed in the vehicle. It was assumed that the toll payments for a manual lane and an AVI lane were the same. The attribute of toll payment, therefore, was not included in the utility function specifications.

Delay Model (Performance Model)

The total average delay, which is the sum of the average waiting delay and the average service delay, was taken as the performance measure in the analysis. Traffic flow theories have used Poisson distribution arrival and exponential distribution service to simulate traffic flow characteristics at toll gates. For a single lane (one server), a reasonable queue model is *M*/*M*/1, based on such distributions. In this case, for a lane with capacity C_i and demand Q_i, the total average delay T_i can be estimated by

$$T_i = \frac{1}{C_i + Q_i}$$

If the vehicles using AVI lanes are distributed evenly among all AVI lanes, the demand for a single AVI lane is Q_a/N_a where the variables were defined previously. From this assumption, the total average delay for an AVI lane is

$$T_a = \frac{1}{C_a - \dfrac{Q_a}{N_a}} \tag{7}$$

where C_a is the capacity of an AVI lane. Equation 7 is also based on the assumption that the lane demand is smaller than the lane capacity. If the demand is greater than the capacity, Equation 7 cannot be used. Under normal operations, the demand should always be smaller than the capacity. This study was to simulate the normal operations. With the same assumption, the total average delay for a manual lane is

$$T_m = \frac{1}{C_m - \dfrac{Q_m}{N_m}} \tag{8}$$

where C_m is the capacity of a manual lane. The total average delay, which combines the total average delays for AVI and manual lanes, can be obtained by using the weighed average of the total average delays for AVI and manual lanes and can be calculated by the following equation:

$$T = \frac{T_m Q_m + T_a Q_a}{Q} \tag{9}$$

The total average delay, T, was used as the performance measure in this analysis. The performance model was used to identify the relationship among lane capacity, market share, and AVI lane configuration.

Equilibrium

The previous two models would result in two curves (Figure 2). The lane choice model generates the demand for AVI and manual lanes, and the delay model estimates the total average delay and was considered the performance in the study. To reach a stationary

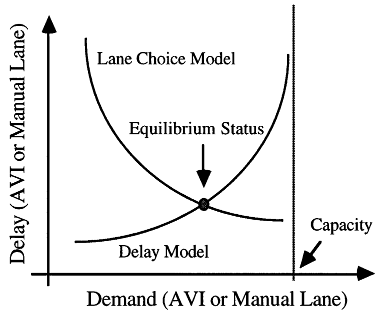

FIGURE 2 Concept of equilibrium.

operational status, an equilibrium status should be obtained. The equilibrium status can be solved in several ways, such as the recurrence method and the curve method. The recurrence method basically performs iterations with given initial values. As the variables become stable, solutions can be obtained. Figure 3 shows a flow chart that presents the procedure to calculate the performance and demand data at the equilibrium status. The curve method develops the demand curve and the performance curve with the variables changed within a reasonable range. The intersecting point of the two curves represents the equilibrium status. This study used the recurrence method to solve the equilibrium status.

Simulation Results

The analysis models described previously were applied to the traffic data collected from the Crosstown Expressway and the Veterans Expressway using iterations. The iterations for each specific lane configuration (with certain numbers of AVI and manual lanes) generated the total average delay at the toll collection stations. Three scenarios were analyzed: manual lanes versus AVI lanes with optical scanner/laser technology, manual lanes versus AVI lanes with RF technology, and manual lanes versus AVI lanes with inductive loop technology. The other AVI technologies were found

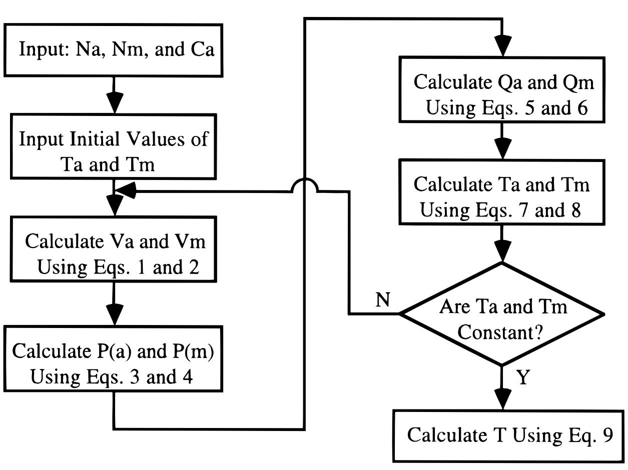

FIGURE 3 Flowchart of solving equilibrium status.

not to be appropriate because of costs and volume thresholds as described previously. The differences between the three scenarios were the lane capacities and the cost associated in the logit model described before. The breakdown of costs of the AVI devices installed in the vehicle consisted of the following: the optical/laser scanner technology costs approximately \$30 (\$3 initial fee for the barcode and \$2 per month); the RF and inductive loop cost about the same, each approximately \$100 (\$34 for the transponder and \$3 per month).

The capacities of a manual lane and an AVI lane were estimated and are presented in Table 1. From Table 1, a capacity of 770 vph was used for a manual lane, 1,200 vph for an AVI lane with optical/laser scanner technology, 1,400 vph for an AVI lane with inductive loop technology, and 1,600 vph for an AVI lane with RF technology. The parameters used in the lane choice model were based on the studies performed by Chang et al. (*10,11*), with the following reasonable values: $k_1 = 0.7$, $k_2 = -2.8$, $k_3 = 0.5$, and $k_4 = -0.02$. It was assumed that drivers on the Crosstown Expressway and the Veterans Expressway had similar lane choice behavior. The same lane choice models were used for the two roads.

On the basis of the data and parameters described previously and a PC-based simulation program developed in this study, simulation analysis was performed to evaluate the three scenarios that would show the effects of different AVI technologies on the delay performance and AVI market share. Tables 3 and 4 present the simulation results including total average delay, T, and AVI market share, $P(a)$. From the tables, it can be seen that as the first few AVI lanes were added to a toll collection station, the total average delay initially increased. However, as more AVI lanes were added, the total average delay dropped significantly and reached the minimum when only one manual lane was kept and the remaining lanes were AVI lanes. Several conclusions can be obtained from these results:

1. The market share curves indicate that the optical/laser scanner AVI technology would attract more drivers than the RF and inductive loop technologies. The RF and inductive loop technologies showed basically similar market share characteristics. This is because the optical/laser scanner requires a lower installation fee than the other two technologies.
2. Generally, the optical/laser scanner AVI technology resulted in better total average delay performance (lower delay curves) in most cases than the other two technologies did. One of the main reasons for this may be the better AVI market share characteristics, which could result in better vehicle distribution among the toll gate lanes. Again, the RF and inductive loop technologies presented basically similar delay performance.
3. When only one manual lane was kept and other lanes were AVI lanes, the delay reached the minimum. From simulation results, it can be seen that the RF technology resulted in the lowest minimum delay in all cases. Since the RF technology generates the highest AVI lane capacity, compared with the other two technologies, this conclusion is reasonable and was expected.

COST-BENEFIT ANALYSIS OF AVI TECHNOLOGIES

A cost-benefit analysis on applications of AVI technologies on toll roads is highly desirable for the planning and design of AVI lanes.

TABLE 3 Total Average Delay and AVI Market Share Data, Crosstown Expressway

		Optical/Laser Scanner				Inductive Loop				Radio Frequency			
		No. of Lanes		Total Ave. Delay (Sec)	AVI Market Share (%)	No. of Lanes		Total Ave. Delay (Sec)	AVI Market Share (%)	No. of Lanes		Total Ave. Delay (Sec)	AVI Market Share (%)
		AVI	Manual	T	P(a)	AVI	Manual	T	P(a)	AVI	Manual	T	P(a)
Crosstown Expressway	Morning Peak Hour	0	8	11.2	0.0	0	8	11.2	0.0	0	8	11.2	0.0
		1	7	11.6	7.5	1	7	13.2	2.2	1	7	13.2	2.2
		2	6	11.2	18.3	2	6	16.1	6.7	2	6	16.0	7.0
		3	5	9.1	36.0	3	5	16.9	18.0	3	5	16.6	18.2
		4	4	7.0	57.2	4	4	13.2	35.8	4	4	12.8	36.1
		5	3	6.0	76.6	5	3	8.6	55.8	5	3	8.2	56.1
		6	2	5.5	89.4	6	2	5.8	74.4	6	2	5.2	74.8
		7	1	5.1	96.0	7	1	4.6	88.2	7	1	4.0	88.4
	Afternoon Peak Hour	0	7	10.2	0.0	0	7	10.2	0.0	0	7	10.2	0.0
		1	6	9.9	11.0	1	6	11.7	3.3	1	6	11.6	3.4
		2	5	9.2	25.0	2	5	13.7	9.6	2	5	13.6	9.7
		3	4	7.4	45.7	3	4	13.5	23.8	3	4	13.2	24.1
		4	3	6.0	67.5	4	3	10.2	44.4	4	3	9.8	44.7
		5	2	5.3	84.2	5	2	6.9	65.8	5	2	6.4	66.1
		6	1	4.9	93.5	6	1	5.1	83.4	6	1	4.5	83.6

Although the throughput for a given toll collection station depends on the market share that AVI technologies can accomplish and the price that drivers are willing to pay to use that facility, the final design of AVI lane configuration (number of AVI lanes) may depend not only on the throughput, but also on the cost-benefit performance that an AVI technology could generate. It is, therefore, essential to investigate the effects of different AVI technologies on the cost-benefit performance.

Cost and Benefit Considerations

Costs related to a roadway toll collection station can be divided into three categories: agency cost (investment, operating, and maintenance costs); user cost (delay and fuel consumption costs); and society cost (environmental impact cost). Use of AVI technologies will increase the agency cost. However, since AVI technologies may be able to reduce the total average delay at a toll collection station, AVI

TABLE 4 Total Average Delay and AVI Market Share Data, Veterans Expressway

		Optical/Laser Scanner				Inductive Loop				Radio Frequency			
		No. of Lanes		Total Ave. Delay (Sec)	AVI Market Share (%)	No. of Lanes		Total Ave. Delay (Sec)	AVI Market Share (%)	No. of Lanes		Total Ave. Delay (Sec)	AVI Market Share (%)
		AVI	Manual	T	P(a)	AVI	Manual	T	P(a)	AVI	Manual	T	P(a)
Veterans Expressway	Morning Peak Hour	0	9	7.5	0.0	0	9	7.5	0.0	0	9	7.5	0.0
		1	8	7.8	4.0	1	8	8.1	1.1	1	8	8.0	1.0
		2	7	7.8	10.3	2	7	8.7	2.9	2	7	8.7	3.0
		3	6	7.2	23.5	3	6	9.3	7.8	3	6	9.3	7.9
		4	5	6.0	44.2	4	5	9.0	19.1	4	5	8.9	19.4
		5	4	5.0	66.9	5	4	7.3	38.3	5	4	7.0	38.7
		6	3	4.6	84.1	6	3	5.2	60.9	6	3	4.9	61.4
		7	2	4.3	93.4	7	2	4.1	79.9	7	2	3.6	80.2
		8	1	4.1	97.5	8	1	3.6	91.3	8	1	3.1	91.5
	Afternoon Peak Hour	0	9	6.7	0.0	0	9	6.7	0.0	0	9	6.7	0.0
		1	8	6.8	3.8	1	8	7.0	1.0	1	8	7.0	1.0
		2	7	6.8	9.8	2	7	7.4	2.7	2	7	7.4	2.8
		3	6	6.4	22.7	3	6	7.7	7.3	3	6	7.7	7.4
		4	5	5.4	43.6	4	5	7.5	17.8	4	5	7.4	18.0
		5	4	4.6	66.8	5	4	6.3	36.6	5	4	6.1	37.0
		6	3	4.2	84.1	6	3	4.8	59.9	6	3	4.5	60.4
		7	2	4.0	93.4	7	2	3.8	79.5	7	2	3.4	80.0
		8	1	3.9	97.5	8	1	3.4	91.2	8	1	3.0	91.4

TABLE 5 Estimated Agency Costs for AVI and Manual Lanes

	AVI Lane	Manual Lane
Investment Cost	AVI Facility: \$3,273/Lane/Year	\$9,000/Lane/Year
	Computer Hardware and Software: \$25,186/Year	
Operating and Maintenance Cost	\$81,000/Lane/Year	\$13,500/Lane/Year

technologies may reduce the user and society costs. For the cost-benefit analysis performed in this paper, the increased amount of the agency cost due to the use of AVI technologies was considered the cost to be analyzed and defined as ΔC, and the reduced amount of user and society costs was considered the "benefit" and defined as ΔB. Mathematically,

$$\Delta C = C \text{ (agency cost with some AVI lanes)} - C \text{ (agency cost with all manual lanes)}$$

$$\Delta B = C \text{ (user/society costs with all manual lanes)} - C \text{ (user/society costs with some AVI lanes)}$$

The performance measure used in this analysis was the ratio of benefit over cost, or $\Delta B/\Delta C$, where the unit of ΔC was in millions of dollars (10^6\$). A different combination of manual and AVI lanes would result in different cost and benefit performance, as would different AVI technologies.

Past studies have provided some useful information about the agency costs related to toll collection station with manual and/or AVI lanes (*8,10*). The study performed by CUTR provided cost estimates of an AVI lane (*8*), such as

Initial investment of AVI facility
= \$33,975/lane, or \$3,273/lane/year

Initial computer hardware and software cost
= \$261,425, or \$25,186/year

Operating and maintenance cost = \$81,000/lane/year

The equivalent yearly costs associated with AVI facility and computer costs were based on a 15-year life cycle and an interest rate of 5 percent. Using the cost data provided elsewhere (*8,10*), the agency cost data were estimated and are presented in Tables 5 and 6.

It is difficult to quantify user and society costs. Practically, the total average delay, T, can be used as a measure for user and society costs. The dollar amount of the costs associated with the user and society costs can be converted from T multiplied by a coefficient k with a unit of \$/time, or

$$C(\text{user/society costs in unit of \$}) = kT$$

To compare the relative cost-benefit performance of AVI technologies and AVI lane usage, the coefficient k does not have to be known. In this case, a practically useful indicator of the benefit of using AVI lanes could be the reduced total average delay T multiplied by a constant k. The benefit ΔB defined in this analysis, therefore, can be obtained by

$$\Delta B = kT(\text{with all manual lanes}) - kT(\text{with some AVI lanes}) = k\Delta T$$

where

$$\Delta T = T(\text{with all manual lanes}) - T\text{ (with some AVI lanes)}$$

As indicated in Tables 3 and 4, in some cases the total average delay with the use of AVI lane(s) was greater than the total average delay without AVI lanes, resulting in negative ΔT and negative $\Delta B/\Delta C$ ratio. The AVI lane configuration resulting in negative $\Delta B/\Delta C$ ratio would not be recommended.

Analysis Results

Table 7 presents cost-benefit analysis results. The main factors affecting the $\Delta B/\Delta C$ ratio were AVI lane configuration and AVI technology types. This table provides some indication for selecting AVI lane configuration and AVI technologies. Practically, the

TABLE 6 Cost-Benefit Analysis Results, Crosstown Expressway

		Optical/Laser Scanner					Inductive Loop					Radio Frequency				
		No. of Lanes		Increased Cost	Decreased Delay	Benefit/Cost Ratio	No. of Lanes		Increased Cost	Decreased Delay	Benefit/Cost Ratio	No. of Lanes		Increased Cost	Decreased Delay	Benefit/Cost Ratio
		AVI	Manual	$\Delta C(10^6\$)$	ΔT (Sec)	$k\Delta T/\Delta C$	AVI	Manual	$\Delta C(10^6\$)$	ΔT (Sec)	$k\Delta T/\Delta C$	AVI	Manual	$\Delta C(10^6\$)$	ΔT (Sec)	$k\Delta T/\Delta C$
Crosstown Expressway	Morning Peak Hour	1	7	.0870	-0.36	-4.14k	1	7	.0870	-1.99	-22.88k	1	7	.0870	-1.97	-22.65k
		2	6	.1487	-0.01	-0.07k	2	6	.1487	-4.88	-32.81k	2	6	.1487	-4.80	-32.27k
		3	5	.2105	2.10	9.98k	3	5	.2105	-5.64	-26.79k	3	5	.2105	-5.40	-25.65k
		4	4	.2723	4.22	15.50k	4	4	.2723	-1.96	-7.20k	4	4	.2723	-1.57	-5.77k
		5	3	.3341	5.25	15.72k	5	3	.3341	2.58	7.72k	5	3	.3341	3.07	9.19k
		6	2	.3958	5.72	14.45k	6	2	.3958	5.44	13.74k	6	2	.3958	6.01	15.18k
		7	1	.4576	6.11	13.35k	7	1	.4576	6.64	14.51k	7	1	.4576	7.26	15.87k
	Afternoon Peak Hour	1	6	.0870	0.23	2.64k	1	6	.0870	-1.50	-17.25k	1	6	.0870	-1.47	-16.90k
		2	5	.1487	0.99	6.66k	2	5	.1487	-3.48	-23.40k	2	5	.1487	-3.38	-22.73k
		3	4	.2105	2.77	13.16k	3	4	.2105	-3.31	-15.72k	3	4	.2105	-3.06	-14.54k
		4	3	.2723	4.17	15.31k	4	3	.2723	-0.02	-7.35k	4	3	.2723	0.37	1.36k
		5	2	.3341	4.84	14.49k	5	2	.3341	3.30	9.88k	5	2	.3341	3.80	11.38k
		6	1	.3958	5.26	13.29k	6	1	.3958	5.07	12.81k	6	1	.3958	5.64	14.25k

TABLE 7 Cost-Benefit Analysis Results, Veterans Expressway

		Optical/Laser Scanner					Inductive Loop					Radio Frequency				
		No. of Lanes		Increased Cost	Decreased Delay	Benefit/ Cost Ratio	No. of Lanes		Increased Cost	Decreased Delay	Benefit/ Cost Ratio	No. of Lanes		Increased Cost	Decreased Delay	Benefit/ Cost Ratio
		AVI	Manual	$\Delta C(10^6\$)$	ΔT (Sec)	$k\Delta T/\Delta C$	AVI	Manual	$\Delta C(10^6\$)$	ΔT (Sec)	$k\Delta T/\Delta C$	AVI	Manual	$\Delta C(10^6\$)$	ΔT (Sec)	$k\Delta T/\Delta C$
Veterans Expressway	Morning Peak Hour	1	8	.0870	-0.21	-2.41k	1	8	.0870	-0.51	-5.86k	1	8	.0870	-0.50	-5.75k
		2	7	.1487	-0.28	-1.88k	2	7	.1487	-1.18	-7.93k	2	7	.1487	-1.16	-7.80k
		3	6	.2105	0.34	1.62k	3	6	.2105	-1.76	-8.36k	3	6	.2105	-1.71	-8.12k
		4	5	.2723	1.57	5.77k	4	5	.2723	-1.47	-5.40k	4	5	.2723	-1.35	-4.96k
		5	4	.3341	2.54	7.60k	5	4	.3341	0.28	0.84k	5	4	.3341	-0.51	-1.53k
		6	3	.3958	2.99	7.55k	6	3	.3958	2.31	5.84k	6	3	.3958	2.65	6.69k
		7	2	.4576	3.23	7.06k	7	2	.4576	3.49	7.63k	7	2	.4576	3.92	8.57k
		8	1	.5194	3.42	6.58k	8	1	.5194	3.97	7.64k	8	1	.5194	4.44	8.55k
	Afternoon Peak Hour	1	8	.0870	-0.11	-1.26k	1	8	.0870	-0.31	-3.56k	1	8	.0870	-0.30	-3.45k
		2	7	.1487	-0.12	-0.81k	2	7	.1487	-0.69	-4.64k	2	7	.1487	-0.68	-4.57k
		3	6	.2105	0.35	1.66k	3	6	.2105	-0.99	-4.70k	3	6	.2105	-0.95	-4.51k
		4	5	.2723	1.28	4.70k	4	5	.2723	-0.76	-2.79k	4	5	.2723	-0.67	-2.46k
		5	4	.3341	2.09	6.26k	5	4	.3341	0.42	1.26k	5	4	.3341	0.61	1.83k
		6	3	.3958	2.50	6.32k	6	3	.3958	1.95	4.93k	6	3	.3958	2.24	5.66k
		7	2	.4576	2.71	5.92k	7	2	.4576	2.92	6.38k	7	2	.4576	3.30	7.21k
		8	1	.5194	2.86	5.51k	8	1	.5194	3.34	6.43k	8	1	.5194	3.76	7.24k

benefit/cost ratio has been used for planning process in many engineering projects. Table 8 summarizes the optimal selection of AVI lane configuration with highest $\Delta B/\Delta C$ ratio values. The information presented in Table 7 can be used for further evaluation of AVI technologies.

CONCLUSIONS

This paper presents preliminary analyses on toll collection stations with AVI technologies. The results from the preliminary analyses could be used for the planning and design processes of AVI lanes used for toll services. The analysis procedure could be used for other similar projects related to AVI technology applications. However, more efforts will be needed to improve the lane choice model and delay model. More detailed survey on drivers' behavior in selecting AVI lanes should be performed to generate better utility functions. Cost information related to cost-benefit analysis was limited. More quantified data need to be obtained for future study.

TABLE 8 Optimal AVI and Manual Lane Distribution Based on Benefit-Cost Ratio

		Optical/Laser Scanner	Inductive Loop	Radio Frequency
Crosstown Expressway	Morning Peak Hour	5 AVI Lanes 3 Manual Lanes	7 AVI Lanes 1 Manual Lanes	7 AVI Lanes 1 Manual Lanes
	Afternoon Peak Hour	4 AVI Lanes 3 Manual Lanes	6 AVI Lanes 1 Manual Lanes	6 AVI Lanes 1 Manual Lanes
Veterans Expressway	Morning Peak Hour	5 AVI Lanes 4 Manual Lanes	8 AVI Lanes 1 Manual Lanes	7 AVI Lanes 2 Manual Lanes
	Afternoon Peak Hour	6 AVI Lanes 3 Manual Lanes	8 AVI Lanes 1 Manual Lanes	8 AVI Lanes 1 Manual Lanes

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